ANALISI SPERIMENTALE DI COLLEGAMENTI BULLONATI A TAGLIO DI ELEMENTI TUBOLARI PER SCAFFALATURE

EXPERIMENTAL INVESTIGATION OF SHEAR BOLTED CONNECTIONS FOR TUBULAR RACKING STRUCTURES

Massimo Latour, Gianvittorio Rizzano
University of Salerno
Department of Civil Engineering
Salerno, Italy
mlatour@unisa.it , g.rizzano@unisa.it

Marina D'Antimo, Jean-François Demonceau,
Jean-Pierre Jaspart,
University of Liege
Department of Architecture, Geology,
Environment and Costructions
Liège, Belgium
m.dantimo@ulg.ac.be, jfdemonceau@ulg.ac.be,
jean-pierre.jaspart@ulg.ac.be

ABSTRACT

The competition in the field of storage racking structures is so that the companies proposing structural solutions for such structures are always looking for an optimisation of the structural elements, through the use of optimized thin wall members, and for an optimisation on site, by proposing easy and cheap connections to limit the time of construction. Within this framework, a simple connection with long bolts for tubular racking structures represents an interesting solution whose shear resistance is not covered by the rules provided by the current EC3. In order to verify the possibility to extend the formulations given in EC3 for connections between plates elements to this kind of connection solution in the present paper the results of an experimental campaign on 24 bolted connections, between hollow tube and long through bolts, are presented and analyzed. In particular the attention is focused on the bearing failure mode around the tube's hole due to bolt's shank contact pressure. The performed analyses evidenced, preliminarily, that Eurocode 3 gives conservative values for the prediction of the bearing resistance.

SOMMARIO

La forte competizione nel campo delle scaffalature di stoccaggio spinge le aziende a proporre soluzioni finalizzate alla ottimizzazione degli elementi strutturali, attraverso l'uso di appropriati elementi in parete sottile, e dei collegamenti per i quali si cercano tipologie facili da montare in cantiere in modo da risultare più economiche riducendo il tempo di costruzione. In tale contesto, una soluzione interessante per le scaffalature con elementi tubolari è rappresentata da connessioni

con bulloni lunghi la cui resistenza al taglio non è coperta dalle regole codificate nella versione attuale dell'EC3. Al fine di verificare la possibilità di estendere le formulazioni riportate nell' EC3 per le connessioni a taglio tra piatti a questa tipologia di collegamento, nel presente lavoro vengono presentati ed analizzati i risultati di una campagna sperimentale su 24 connessioni di elementi tubolari con piatti mediante bulloni lunghi passanti. In particolare l'attenzione è focalizzata sulla modalità di rottura a rifollamento della zona del tubo vicino al foro per effetto della pressione esercitata dal gambo del bullone. Le analisi effettuate hanno evidenziato, in via preliminare, che l'Eurocodice 3 fornisce valori conservatori della resistenza a rifollamento.

1 INTRODUCTION

With reference to steel storage racks, the connections between the structural members play an important role on the global structural behavior and on the cost. Classically, the connection between uprights columns and beams is performed by means of pin connections obtained by punching the pins in a cold formed connector welded at the end of the beam. More recently, the increasing competition in the field of racking structures has spurred the companies to offer commercial solutions more economical by simplifying the connection details in order to reduce the fabrication and the assembly costs. In fact the typical tab connection requires the manufacturing of the beam end connector by punching the tabs in the cold-formed connector, welding the connector to the beam and attaching a locking pin system to the connector. In [1,2,3] it has been evidenced that an economical alternative solution of connection can be represented by bolted moment connections between cold-formed steel members adopting gusset plates. Nevertheless, for design and check purposes, this typology of connection is not among the cases regulated by Eurocode 3 Part 1.8. In fact, the formulations provided by Eurocode cover the shear resistance of connections between two (or three) plates in direct contact with the bolt head or the nut, which creates a kind of "confinement" in the zone of the plate in direct contact with the bolts (Fig.1a).
Therefore, it is important to understand if the formulations present in the current version of Eurocode 3 devoted to the prediction of the bearing resistance of plates can be applied also to the case of connections of tubular members of racking structures. In this case, the inner face of the tubular profile is in contact with the long bolt but the nut is not in direct contact with the member face and local instability can occur. Therefore, the resistance of the tube's plate and, in particular, its resistance to bearing, could be significantly influenced by local buckling phenomena and, as consequence, it could be lower than the one predicted through the rules recommended by Eurocode 3.
In order to analyze this phenomenon, an experimental campaign on 24 bolted connections, between hollow tube and long through bolts, has been performed. Then, by means of a comparison between the experimental values and the ones predicted with EC3 formulations, the accuracy of the application of the codified approach to shear connections of tubular profiles has been verified.

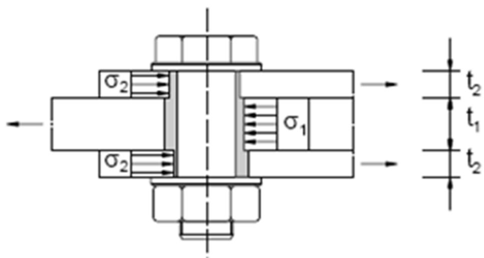
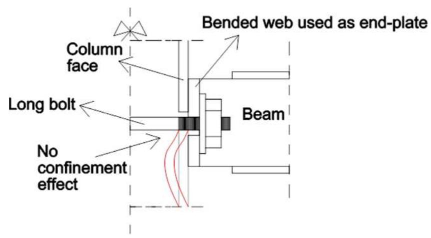


Plate connections (a)



Tube-to-plate-connections (b)

Fig. 1. Shear connections

2 EXPERIMENTAL INVESTIGATION

In order to evaluate the behaviour of simple connections realized fastening tubular members by means of long bolts, an experimental programme constituted by 24 specimens was performed at the Laboratory of the University of Liège.

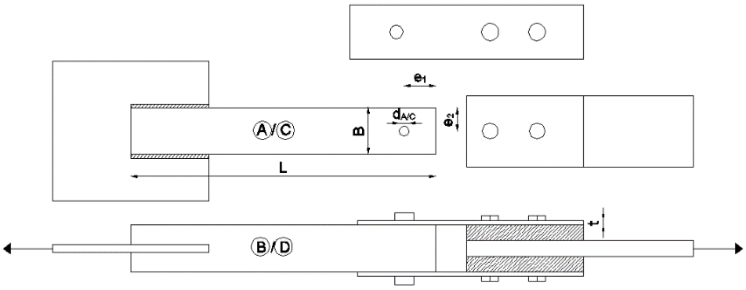
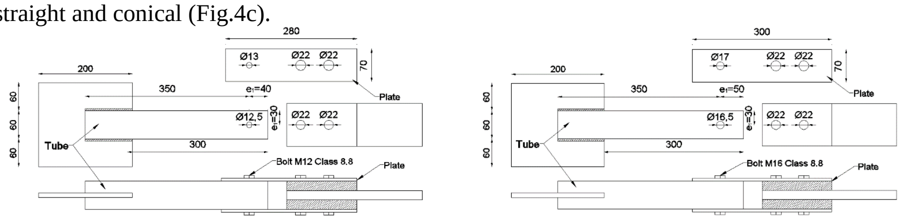


Fig. 2. Joint assembly

The layout of the specimens consists of a square tube fastened to a couple of plates by means of a long bolt, subjected to a monotonic tensile load (Fig.2). The 24 specimens are divided into six groups, according to the bolt diameter, thickness of the tube and material typology. In particular, two different materials were tested, namely HX420LAD (f_y=min.420/max.520 MPa) and S235 (f_y=235 MPa), three different tube thicknesses (2 mm, 2.5 mm and 4 mm) and two bolt diameters were considered (M12 and M16). All the bolts were 8.8 class and were not preloaded before executing the test. The specimens were connected to the loading machine by means of steel plates, on one side welded to the tube and, on the other side, bolted to the specimen (Fig.2). Before executing the tests, the sides of the tubes were marked with a letter. In particular, the holed sides were called A or C and the two other sides were called B or D.

In Table 1 the material grades and the actual dimensions of all the specimens are summarized. In particular, in such a table the values of the parameters d_A and d_C, which are the minimum dimensions of the hole diameters (on the side A and C of the profile) and of the parameter d_N, which is the nominal dimension of the hole, are also given. The experimental setup and the nominal geometry of the specimens is also summarized in Fig.3a for the experimental series HX-2-M12, HX-2.5-M12 and S235-4-M12, and in Fig.3b for the experimental series HX-2-M16, HX-2.5-M16 and S235-4-M16.

As reported in Table 1, the holes of the specimens were realized in some cases by means of drilling and in some cases by means of punching technique. In particular, when the specimens were drilled, the shape of the hole was cylindrical (Fig.4a), while when they were punched, the diameter of the hole was not constant along the thickness of the tube and it was conical (Fig.4b) or combined straight and conical (Fig.4c).



a) *HX-2-M12, HX-2.5-M12 and S235-4-M12* ***b)*** *HX-2-M16, HX-2.5-M16 and S235-4-M16*

Fig. 3. Specimens' nominal geometry

Table 1. *Specimens' geometrical and mechanical properties*

	TUBE		*L[mm]*	*B[mm]*	*d_N[mm]*	*Holing procedure*	*d_A[mm]*	*d_C[mm]*	*t[mm]*	*e_1[mm]*	*e_2[mm]*
HX-2-M16	**HX420LAD**	1	399	60.15	16.5	Punched	16.59	16.66	2.04	50.26	29.67
	Thickness	2	398.8	60.16	16.5	Punched	16.50	16.51	2.11	48.66	29.68
	2mm, bolts	3	399.5	60	16.5	Punched	16.50	16.53	2.06	49.02	29.72
	M16	4	399.3	59.8	16.5	Punched	16.53	16.50	2.07	49.11	29.76
HX-2-M12	**HX420LAD**	5	389.9	60	12.5	Punched	13.28	12.9	2.03	39.27	29.92
	Thickness	6	390.2	59.8	12.5	Punched	12.89	13.05	2.06	40.00	30.21
	2mm,bolts	7	390.1	59.9	12.5	Punched	12.84	12.93	2.09	39.93	30.15
	M12	8	389.6	59.9	12.5	Punched	12.97	12.93	2.04	39.86	30.15
HX-2.5-M12	**HX420LAD**	9	391.2	60	12.5	Punched	12.55	12.64	2.57	39.60	29.84
	Thickness	10	388.7	60.1	12.5	Punched	12.46	12.56	2.55	40.00	29.99
	2.5mm,bolts	11	390.4	60	12.5	Punched	12.46	12.85	2.51	41.94	29.70
	M12	12	390.3	60.1	12.5	Punched	12.66	12.30	2.55	40.82	29.69
HX-2.5-M16	**HX420LAD**	13	399	59.9	16.5	Punched	16.59	16.49	2.57	49.58	29.93
	Thickness	14	399	60.1	16.5	Punched	16.98	16.45	2.54	51.67	30.02
	2.5mm,bolts	15	398.9	60.1	16.5	Punched	16.99	16.50	2.62	50.87	30.00
	M16	16	399.1	60	16.5	Punched	16.76	16.45	2.55	49.45	30.00
S235-4-M12	**S235**	1	391.7	60.5	12.5	Drilled	12.39	12.53	3.85	33.17	30.30
	Thickness	2	391.3	60.4	12.5	Drilled	12.41	12.51	3.87	33.36	30.39
	4mm,bolts	3	391.6	60.4	12.5	Drilled	12.57	12.56	3.85	33.05	30.49
	M12	4	391.5	60.4	12.5	Drilled	12.46	12.53	3.79	34.07	30.35
S235-4-M16	**S235**	5	391.4	60.3	16.5	Drilled	17.24	17.29	3.8	41.48	30.39
	Thickness	6	391.5	60.6	16.5	Drilled	17.27	17.40	3.8	37.61	30.40
	4mm,bolts	7	391	60.5	16.5	Drilled	17.31	17.37	3.8	40.61	30.49
	M16	8	390.1	60.6	16.5	Drilled	17.26	17.28	3.8	41.27	30.25

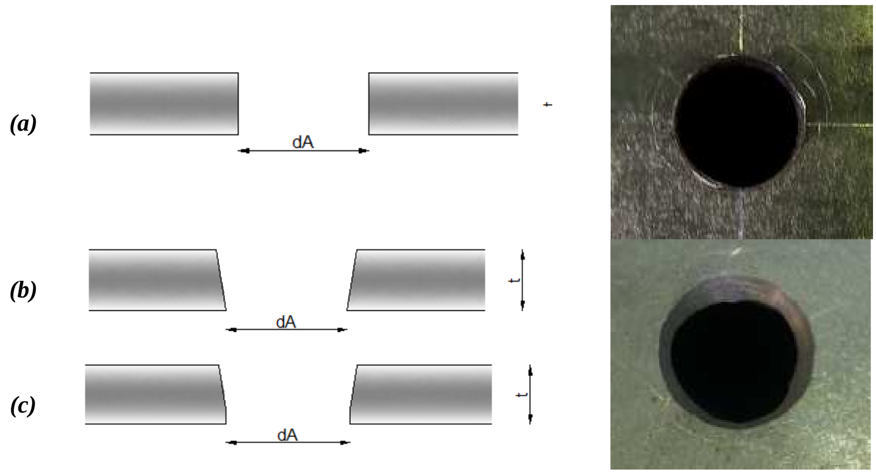


Fig. 4. Shape of the holes: a) drilled hole, b) punched hole with conical shape, c) punched hole with straight and conical edges

As better described in the next sections, the shape of the hole can significantly influence the elastic behaviour of the connections and, therefore, in the following analyses when reference is made to the models called "initial", a simplified shape like the one reported in Fig.4b with a minimum value of the hole diameter equal to the measured one and a maximum diameter equal to the minimum one plus a clearance of 0.5 mm is considered [4]. Conversely, when reference is made to the models called "ideal", the shape of the hole is modelled as perfectly cylindrical as reported in Fig. 4a. Preliminarily, in order to define the actual mechanical properties of the specimens' materials, eleven coupon tests have been carried out. The tests have been performed by means of a Zwick/Roell z100 testing machine under pure tensile loads. All the geometrical properties of the coupons are summarized in Table 2 together with the experimental engineering values of yield (or proof stress) and ultimate strength. In particular the initial and final values of the specimens' elongations are reported together with the width and thickness.

Table 2. Geometrical and mechanical properties of the Tested specimens

		Initial values			*Final values*				
	Test	***Length [mm]***	***Width [mm]***	***Thickness [mm]***	***Length [mm]***	***Width [mm]***	***Thickness [mm]***	***f_y (0.2%) [MPa]***	***f_u [MPa]***
Loading plate	***G1***	80.06	20.36	5.99	98.76	17.56	3.47	285.15	385.46
	G2	80.06	20.37	6	100.52	16.67	3.59	287.71	387.23
Tube S235	***TCN 1***	80.07	20.44	3.74	99.03	17.85	2.65	404.01	429.5
	TCN 2	80.06	20.41	3.72	104.29	14.95	2.67	392.56	423.18
	TCN 3	80.08	20.36	3.76	10542	14.17	2.65	408.26	428
Tube HX420LA D 2mm	***TCG 1***	80.08	20.49	1.97	103.43	14.14	1.64	409.61	499.16
	TCG 2	80.08	20.43	1.97	111.19	13.54	1.63	389.55	491.54
	TCG 3	80.09	20.44	1.97	112.98	13.37	1.65	397.39	499.84
Tube HX420LA D 2.5mm	***TCG A***	80.06	19.87	2.44	99.85	15.97	1.72	431.07	509.74
	TCG B	80.06	19.85	2.43	101.35	16.19	1.67	439.3	508.55
	TCG C	80.06	19.85	2.45	101.84	16.05	1.79	433.52	510.17

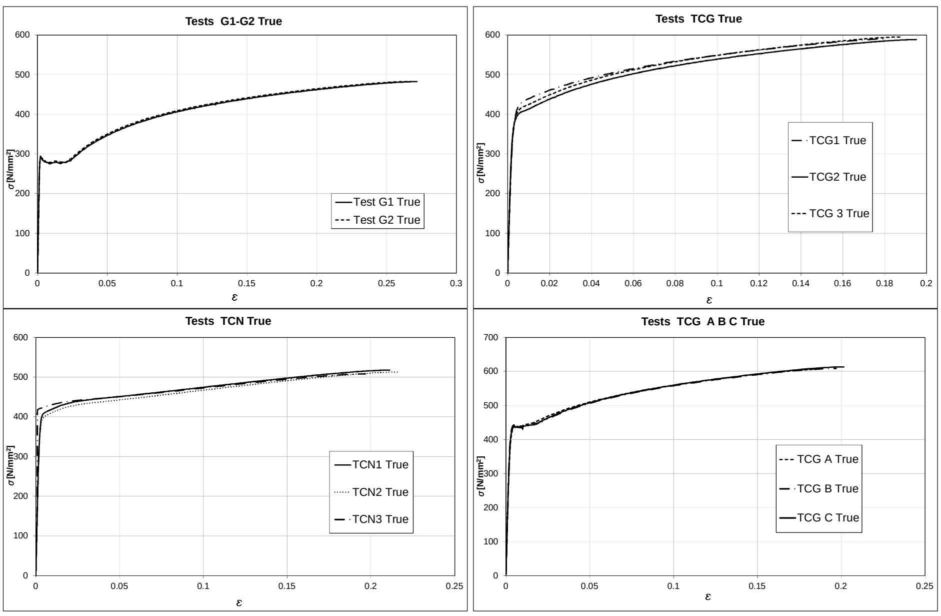


Fig. 5. Stress Strain curves of material coupon tests

Starting from the results of the tests, the true stress-true strain response of the materials has been determined by following the procedure provided in [5]. In particular, in order to obtain the curves reported in Fig.5 the engineering values of stress (σ_E) and strain (ε_E) have been converted in terms of effective stress and logarithmic strain according to the following equations:

$$\sigma_T = \sigma_E(1 + \varepsilon_E) \quad (1)$$

$$\varepsilon_T = ln(1 + \varepsilon_E) \quad (2)$$

2.1 Experimental results

The tests on the connections have been performed by means of a Schenck RME 600 under monotonic loading conditions. The loads have been applied under displacement control following a quasi-static protocol aimed at defining the initial stiffness of the connection and the force-displacement response up to failure. In particular, in the initial phase, the load has been applied with a speed equal to 1 mm/min and, after executing an unloading and reloading, with a speed of 2 mm/min for specimens' series HX420LAD (1-16) and 3 mm/min for specimens' series S235 (1-8). The displacement of the connections has been measured by employing three transducers. An external transducer to evaluate the global response of the connection and two transducers directly applied on the specimen to evaluate the local elongation of the holes (Fig.6).
In Fig.7 the experimental results of all the tests have been represented in terms of force and displacement. The displacements reported in such graphs have been obtained starting from the average value provided by two transducers directly applied on the specimen.
The force-displacement behaviour observed was very similar for all the tested connections. In fact, they were characterized by an initial stiffness significantly different for the four specimens of the same group, evidencing a variability of the initial deformability of the holes probably due to the different magnitude of the imperfections. In addition, the stiffness observed after the unloading/reloading was significantly higher than the initial one, probably due to the recovery of the imperfections after the first plasticization of the holes. It is useful to observe that, in a real structure, the initial stiffness appears only once, i.e. at the first loading cycle, while the unloading/reloading stiffness is representative of all the other loading conditions to which is subjected the joint after the initial slippage of the connection.
After the elastic phase, all the specimens provided a significant strain hardening behaviour up to the failure of the joint, which was mainly related to the progressive hole ovalization (Fig.7).

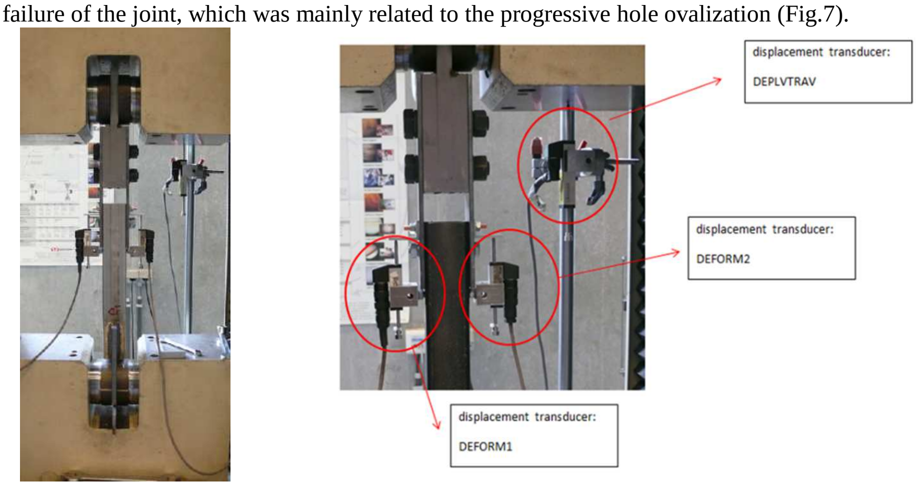


Fig.6. Experimental set-up: Specimen and transducers' location

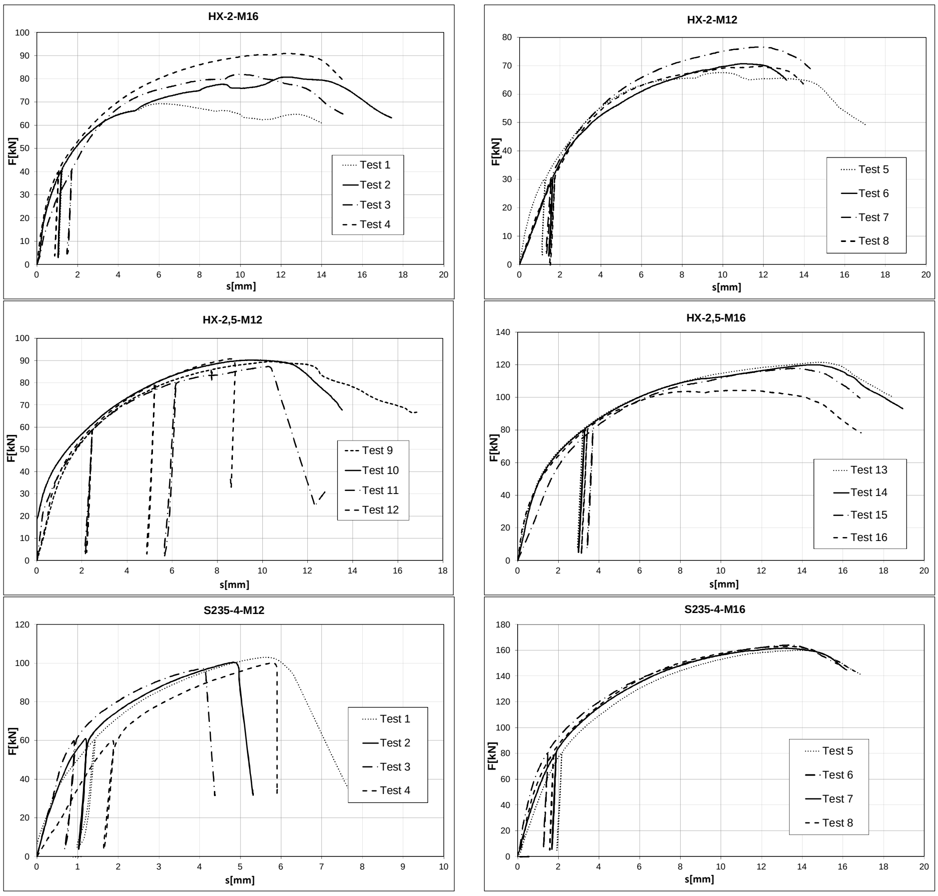


Fig. 7. Experimental force-displacement curves

The failure modes exhibited by the connections have been of two types: the bolt shear failure or the bearing failure with out-of-plane local buckling of the tube in the zone around the hole (Fig.8). In all the tested specimens the tensile failure of the tube or the shear failure of the plate was never observed, highlighting that the distance from the edges parallel and orthogonal to the load was sufficiently large to avoid a global failure of the tubes' plates.

The failure mode was due to the bearing collapse of the tube with the formation of two cracks developing at the edge of the bolt hole (Fig.8a-8b) or to the bolt in shear, with the complete fracture of the threaded section of the bolt in correspondence of the tube hole (Fig.8c).

In Table 3 the maximum values of the load achieved in each test, the hole length at the end of the tests and the failure modes are summarised. The collapse of the bolt in shear was observed only for tests HX420LAD (11-12) and for specimens' series S235 (1-4). In Table 3 the ultimate shear resistance of the bolts, evaluated according to EC3 is also provided:

$$F_{v,Rd} = \frac{\alpha_v f_{ub} A_b}{\gamma_{M2}} \tag{3}$$

a) Bearing failure: fracture around the hole   b) Bearing failure Local buckling of the tube   c) Bolt shear failure

Fig. 8. Typical failure modes of the specimens

where α_b = 0.6 (bolt grade 8.8), A_b is the tensile area of the bolt, f_{ub} is the ultimate strength of the bolts and γ_{M2} is the partial safety factor assumed equal to 1. From the results summarized in Table 3 it is possible to observe that in case of specimens' series S235 (1-4), the bolts' failure occurred at a resistance value very close to the theoretical one with a code prediction on safe side. Conversely, in case of tests HX420 (11-12) the failure of the bolts occurred at a load value lower than the resistant one. This result can be probably justified by the unloading and reloading executed at a high value of the displacement, due to a technical problem occurred during the tests (Fig.7).

Table 3. Results of experimental tests

		N° specimen	**Hole length[mm]**		**Failure mode**	**$F_{max,Exp}$ [kN]**	**$F_{max,Exp,ave}$ [kN]**	**$F_{max,FEM}$ "initial" [kN]**	**$F_{max,BOLT}$ [kN]**
			***Side* A**	***Side* C**					
HX-2-	**"Tubes HX420LAD": Thickness 2mm, bolts M16**	1	29.66	28.51	*Bearing*	69.32	80.75	72.98	171
		2	32.32	33.32	*Bearing*	80.78			
		3	29.72	30.91	*Bearing*	81.95			
		4	30.46	29.48	*Bearing*	90.96			
HX-2-	**"Tubes HX420LAD": Thickness 2mm, bolts M12**	5	28.14	29.15	*Bearing*	67.64	71.21	65.70	94.70
		6	24.53	24.83	*Bearing*	70.75			
		7	24.97	26.67	*Bearing*	76.62			
		8	25.31	26.1	*Bearing*	69.84			
HX-2.5-M12	**"Tubes HX420LAD": Thickness 2.5 mm, bolts M12**	9	26.81	28.83	*Bearing*	89.62	89.50	77.13	94.70
		10	24.39	25.62	*Bearing*	90.25			
		11	22.04	19.94	*Bolt failure*	87.36			
		12	20.13	18.08	*Bolt failure*	90.76			
HX-2.5-	**"Tubes HX420LAD": Thickness 2.5 mm, bolts M16**	13	34.11	31.71	*Bearing*	121.60	115.96	107.9	171
		14	34.59	32.62	*Bearing*	120.04			
		15	22.36	21.05	*Bearing*	117.83			
		16	30.32	32.11	*Bearing*	104.37			
S235-4-M12	**"Tubes S235": Thickness 4mm, bolt M12**	1	14.93	17.07	*Bolt failure*	103.06	100.35	80.94	94.70
		2	15.93	14.66	*Bolt failure*	100.39			
		3	14.56	15.3	*Bolt failure*	97.24			

		4	14.79	16.83	*Bolt failure*	100.18			
S235-4-	**"Tubes S235": Thickness 4mm, bolt M16**	5	31.32	29.73	*Bearing*	160.38	162.29	145.42	171
		6	30.5	30.46	*Bearing*	164.08			
		7	29.36	30.95	*Bearing*	161.67			
		8	30.76	29	*Bearing*	163.04			

3 PREDICTION OF THE BEARING RESISTANCE ACCORDING TO EC3 MODEL

As a first step, in order to evaluate the possibility to simply extend EC3 provisions also to the connections analysed in this work, the accuracy of the formulation currently proposed by EC3 has been verified by means of comparison with the experimental results. According to EC3, the resistance of the connection is provided by the minimum value between bolt and bearing resistances. In particular, the bolt resistance can be calculated according to Eq.1, while the bearing resistance can be evaluated starting from the following relationships:

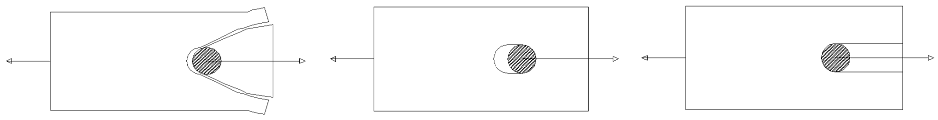
$$F_{b,Rd} = \frac{k\alpha_b f_u t d}{\gamma_{M2}} \quad (4)$$

$$\alpha_b = Min\left(\frac{e_1}{3d_0}; \frac{f_{ub}}{f_u}; 1\right) \quad (5)$$

where, f_u and f_{ub} are the plate and bolt ultimate strength, d and d_0 are the bolt and hole diameter, e_1 is the distance of the hole from the plate free edge and k is equal to 2,5 provided that the distance of the hole from the lateral edge of the plate e_2 is greater than 1,5d. These last equations account for all the basic failure modes normally arising in a simple bolted connection and, in particular, include the failure mechanisms reported in Fig.9, i.e. tear-out failure, bearing failure and shear failure. In particular, the first and last failure modes depicted in Fig.9, namely tear-out and shear failure, normally occur for small distances of the bolt from the free edge due to the achievement along shear planes of the ultimate stress of the material. Conversely, the second failure mode, namely bearing failure, occurs when the distance from the edge is sufficiently large to avoid the occurrence of failure of the plate material. In this case, the bearing forces between bolt and plate cause the ovalization of the hole leading to a localized failure mechanism. For this last mechanism, basing on the experimental results reported in [6], EC3 assumes that the bearing strength can be taken as 2.5 times the ultimate stress of the plate material.

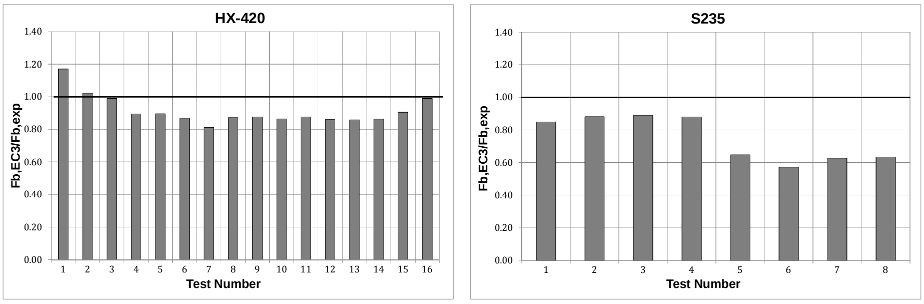
Conversely, for the shear failure mode, EC3 adopts the simple model reported in Fig.9c, where the resistance is evaluated assuming that the length of the longitudinal shear sections is equal to 0.9e_1. This failure mode leads to the additional reduction of the resistance provided by Eq.3 when e_1 is lower than 3d_0. Dealing with the tear-out failure mode, EC3 assumes that it can be neglected provided that e_2 is higher than 1.5d_0, which is a condition normally verified in typical connections. The result of the application of the code formulation to the tested specimens is reported in Fig.10 where the ratios between the predicted and the experimental values of the bearing resistance for each test are represented.

The comparison is performed assuming that the partial safety factor is equal to 1 because the measured values of the geometrical and mechanical parameters have been employed. As it is possible to observe from Fig.10, the comparison between the bearing resistance provided by the experimental tests and that predicted by EC3 formulation evidences a good accuracy of the model in the analysed range of variability of the geometrical and mechanical properties.



(a) ***(b)*** ***(c)***

Fig. 9. Tear-out failure (a), Bearing Failure (b), Shear failure(c).



(a) (b)

Fig.10. Accuracy of EC3 model. a) Tubes of HX420LAD steel, thickness 2/2.5 mm; b) Tubes of S235 steel, thickness 4/6 mm

In fact, the average value of the ratio is equal to 0.9 and 0.74, while the standard deviation is equal to 0.08 and 0.13 for the test groups HX420LAD and S235 respectively. Nevertheless, this first comparison highlights also that the prediction is not always on the safe side. In particular, a lower safety of the EC3 model is observed for the specimens characterized by a low value of the tube thickness and bolt diameter ratio. Probably, this result can be due to the fact that the EC3 formulation does not account for the local buckling failure mode which is a phenomenon more significant especially when the local slenderness of the tube's plate is high. Therefore this first comparison, points out the need for a further investigation in the field of low values of the tube thickness.

4 CONCLUSIONS

In this work, the behaviour of shear joints with long bolts passing through thin-walled tubular columns belonging to racking structure has been investigated. On the basis of an experimental campaign performed on this kind of connection it has been recognised that Eurocode 3 provides conservative values of the bearing resistance. Moreover, in correspondence of low values of the tube thickness and bolt diameter ratio, due to the arisement of local buckling phenomena, an improvement of the EC3 approach appears advisable.

REFERENCES

[1] Chung KF, Lau L. "*Experimental investigation on bolted moment connections among cold formed steel members*". Engineering Structures 1999;21(10): 898_911.
[2] Wong MF, Chung KF. "*Structural behaviour of bolted moment connections in cold-formed steel beam_column sub-frames*". Journal of Constructional Steel Research 2002;58(2):253_74.
[3] Lim JBP, Nethercot DA. "*Ultimate strength of bolted moment-connections between cold-formed steel members*". Thin-Walled Structures 2003;41(11): 1019_39.

[4] UNI ENV 1090-2:2011, "*Esecuzione di strutture di acciaio e di alluminio - Parte 2: Requisiti tecnici per strutture di acciaio*".
[5] Faella C., Piluso V. & Rizzano, G., 2000. "*Structural steel semirigid connections: Theory, design and software*". CRC Publishers, Boca Ratón.
[6] Ungermann D., Sedlacek G., , "*Evaluation of test results on bolted connctions in order to obtain strength functions and suitable model factor- Part C, Test Data, Background documentation to Eurocode No.3, Document 6.03*", RWTH-report, Aachen, 1988.
[7] CEN, 2005a. Eurocode 3: Design of steel structures - Part 1-8: *Design of joints. European Committee for Standardization*, CEN, Brussels.